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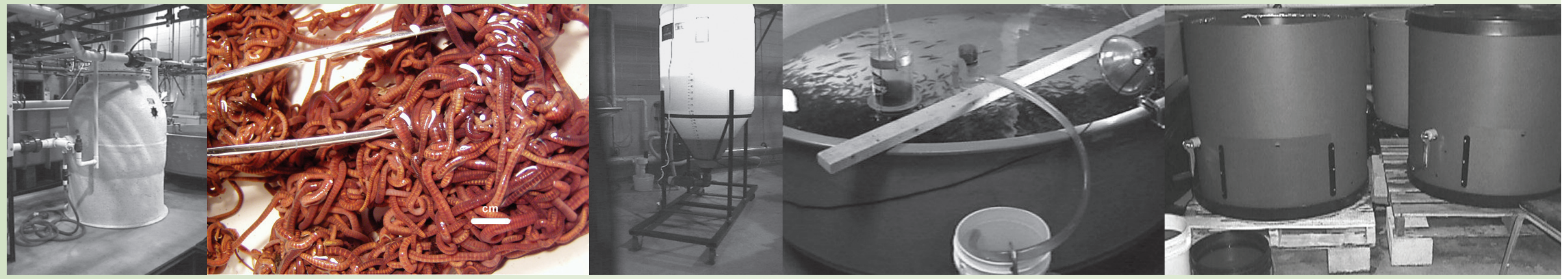

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Recirculating Aquaculture Systems (RAS) use less water than open pond systems and the concentrated wastes generated by fish in RAS are easier to collect and reuse. High operating costs limit RAS use to high-value species production. One strategy to improve productivity and offset the high operating costs is to convert the solid waste from the aquaculture systems to more valuable byproducts.

Conversion of Waste Solids to Valuable Byproducts

Since RAS inherently concentrate and capture solid wastes to a greater extent than other aquaculture systems, they present an excellent potential for beneficial reuse of solid wastes (Yeo et al. 2004). Currently, biosolids from RAS are generally disposed of through diversion to sewage treatment or septic system facilities, and the accumulated biosolids are applied as a soil amendment and low-grade fertilizer. When settling basins are emptied, the waste from large-scale, flow-through production hatcheries is available for land application. The waste from the settling basins is available in larger quantities and will have a variable quality due to age compared to solid waste removed nearly daily in smaller quantities from an RAS in concentrated raw form. Generally, the amount of recovered biosolids from typical North Central Region (NCR) operations is too small to serve as the principal fertilizer for field crop production. An objective of a more integrated or sustainable aquaculture system should be to reuse the waste because it is a valuable resource (Adler et al. 1996; Yeo et al. 2004).

Composting is an alternative to direct land application of aquaculture biosolids. Composting produces a useful soil amendment or planting medium that is a slow release fertilizer with increased soil water holding capacity. Composting involves some additional expense for storing and handling the wastes, but composts have commercial value and can potentially be sold, for profit, as a soil amendment. In addition, the composting helps to stabilize the waste material, reducing odor, oxygen demand, and the volume of the waste. Stabilized finished compost is easier to store and transport for use than raw waste, and application can be delayed for better coordination with crop needs. Composting is also suitable for processing dead fish, spoiled feed, and fish processing residues that aquaculture operations will generate (UWSGI 1992; Fornshell et al. 1998).

Problems Inherent with Conventional Composting

Conventional composting is an accelerated biological oxidation of organic matter, that passes the waste through a "thermophilic" stage (45 to 65°C; 113 to 149°F) where microorganisms (mainly bacteria, fungi, and actinomycetes) break down the waste, generate heat, and release carbon dioxide and water. Conventional composting is conducted by adding high carbon content materials to wastes of high nitrogen content. These materials encourage the composting reaction of these heat- generating (i.e., thermophilic) microbes. The compost mixture needs to be piled high enough (approximately 1.22 m [4 ft] in the NCR) to retain the heat that supports this thermophilic reaction; the high temperature of this reaction also helps to destroy potential disease organisms. The conventional compost pile requires considerable bulk and, in the NCR, is subject to cessation or reduction of activity during the regional cold season.

Heat-generating microbes use oxygen rapidly. Conventional compost piles involve considerable labor since they must be turned frequently to produce adequate ventilation in order to avoid conditions that use up the available oxygen, i.e., "anaerobic" conditions, and shift the microbe activity to production of obnoxious odors. Through composting, organic waste materials are transformed into a homogeneous and stabilized humus-like product with a mild earthy odor.

Worm Composting for Profitable Byproducts from Waste Solids

As an alternative to conventional composting, the use of worms (Edwards and Neuhauser 1988) in the composting process, termed "worm composting" or "vermicomposting", has been increasingly applied to diverse organic wastes (e.g., livestock manures) and offers several advantages that may be appropriate for use by NCR aquaculturists (Sherman-Huntoon 2000). Because of the high moisture content in fish manure, worm composting may be a more suitable stabilization technique, than conventional composting, which requires greater amounts of bulky dry amendments. Vermicomposting is also a biological oxidation and stabilization process for organic material that, in contrast to conventional composting, involves the joint action of earthworms and microorganisms. However, vermicomposting does not depend on a thermophilic stage nor require large piles of bulking agents. Earthworms become the agents of turning, fragmentation, and aeration, consequently avoiding some of the labor associated with turning conventional compost piles. Worm compost tends to be more fine-grained and homogenous than conventional compost and to have superior moisture-retaining properties. Both the worm compost and the worms themselves are salable products that may increase the cost effectiveness of recirculating system rearing strategies. Worm and worm compost production does not involve additional higher energy inputs for pumping water or intense lighting. It can also provide favorable alternatives to disposal of aquaculture biosolids to septic systems or public sewage treatment facilities.

Worm composting provides a superior form of stabilized compost that is more suitable and valuable for potted plant or smaller scale gardening. Worm compost and castings are particularly desired by "organic" growers because of their benefits to soil microflora. Diversion of aquaculture biosolids to worm composting lightens the load to fish farm septic facilities, reduces the size of septic storage facilities needed, and potentially increases the intervals between required maintenance. Readily stored compared to liquid biosolids, stabilized worm compost can avoid the cold season limitations of land application. Although the nitrogen (N), phosphorus (P) and potassium (K) nutrient content of composts is not as high as that of inorganic fertilizers, vermicompost, compost, leachates and compost "teas" (specially brewed solutions that incorporate and proliferate the beneficial microflora of composts and are used by organic gardeners to promote soil health and plant growth) have been demonstrated to benefit the microfloral health of soils, improve the "availability" of nutrients to plants, and aid in suppressing plant disease (Edwards and Burrows 1988; Adler et al. 1996; Atiyeh et al. 2000 & 2001; Hildago et al. 2001).

Vermicomposting beds are typically only about 0.45 m (1.5 ft) deep rather than the approximately 1.22 m (4 ft) depth needed for heat retention in conventional composting. Consequently, the space requirements are more modest and the process can be effectively conducted on a scale from small household bins to large institutional waste disposal size composters, and even done indoors to overcome NCR climatic limitations.

Uses and Value of Vermicompost

The end products of vermicomposting are a highly-valued specialty organic fertilizer, and mature worms that have value either as fish bait or as live fish or pet food. Earthworms have been commercially used to process diverse organic wastes on a large scale worldwide. Because other livestock manures currently are used successfully as feedstock for worms, there is reason to believe that recovered aquaculture biosolids in the form of fish manure, unused feed, or fish processing waste also can be effectively processed through vermicomposting.

The organic worm compost is usually a finely-divided peat-like material with excellent structure, porosity, aeration, drainage, and moisture-holding capacity (Edwards 1982; Edwards and Burrows 1988). Nutrient content differs depending on the parent material. However, worm compost produced from a variety of animal manures has been shown to often have higher levels of most nutrients, except for magnesium, than other commercial compost materials (Edwards and Burrows 1988). It is significant to note that during the processing of wastes by earthworms, many of the nutrients in the compost are changed to forms more readily taken up by plants, such as nitrate, soluble P, and exchangeable potassium, calcium, and magnesium (Edwards and Burrows 1988). A wide range of plants, including many vegetables, bedding plants, flowers, and ornamental shrubs have been successfully grown in worm-worked wastes (Edwards and Burrows, 1988; Atiyeh et al. 2000 &2001; Hidalgo et al. 2001). Seedling emergence tests of tomatoes, cabbage, radishes, and ornamentals tended to be as good or better than in commercial growth medium, and much better than in composted animal wastes with no earthworms (Edwards and Burrows 1988).

Potential commercial markets for worm-worked animal wastes vary from country to country, as do the economic returns (Edwards and Burrows 1988). A 2009 internet search of U.S. retail prices indicates that worm casting compost is sold retail as bagged organic specialty fertilizer from $0.97 to $2.93/kg ($0.44 to $1.33/lb) with the variation being related to quality. Bulk worm castings are sold from $47 to $131/m^3 ($36 to $100/yd^3) (Vermico web site: www.vermico.com/whyworms.htm) . In general, for the high-value market, the product must be produced as a standard material varying little in consistency or nutrient content. For such a product, uniform sources of organic wastes must be available, and the mixture and additives must be in constant proportion. Batch analysis may be needed to ensure standardization of the product. When the product is produced with lower technology and with more variable wastes, its value decreases but so does the cost of production, processing, and packaging (Edwards and Burrows 1988). Biosolids from aquaculture systems provide a consistent, uniform, and fine-grained source of waste that should produce a uniform and high-quality vermicompost.

Cultured Worms as Bait and Live Pet Food

Although a variety of worms, including cultured worms, are used by approximately 50 million North American anglers, the overwhelming proportion of the North American bait market is comprised of the native nightcrawlers or "Dew worm", *Lumbricus terrestris* (Tomlin 1983). Hand-gathered at night by pickers, the large-sized North American nightcrawlers are maintained by wholesalers in large coolers before being shipped to bait dealers. There are no cost-effective means of culturing native nightcrawlers. Consequently, those sold by the bait industry are all from hand-picking operations and held under refrigeration. Smaller-sized cultured worms are sold, but don't command the premium prices that are obtained for larger-sized native nightcrawlers. Although cultured warm-temperature worm species such as "African nightcrawlers", *Eudrilus eugeniae*, can achieve a larger size for use as bait than the smaller red worms, cultured species are still generally smaller than the native nightcrawlers.

Stored under refrigeration, native nightcrawlers don't require supplemental feeding to be maintained as live bait. In contrast, cultured worms die under refrigeration and must be transported at room temperatures, in ventilated containers and periodically offered small quantities of commercial worm food or other suitable alternative organic matter, to survive as live bait. Currently, the bait industry has largely invested in refrigerated transport and storage facilities for North American night crawlers and is not equipped for the needs of the cultured bait worm. Those wishing to market cultured worms may have to develop and explore alternative points of sale to retailers and directly market to anglers. Approximate prices of cultured red worms as quoted in the 2009 internet search are in the range of $33 to $42/ kg ($15 to $19 / lb). Cultured nightcrawlers prices were in the $55 to $59/ kg ($25 to $27/ lb) range.

In addition to having marketable value as bait, earthworms are also suitable as food for fish as well potential specialty animal and pet feed (Edwards and Niederer 1988). Like meat and fish, worm tissue is about 60% protein. The essential amino acid profile of worm tissue is very good for animal feed, contains a preponderance of long-chain fatty acids, has an excellent range of vitamins, is rich in niacin, and is an unusual source of vitamin B12 (Edwards and Niederer 1988). While earthworm protein could be a substitute for fishmeal in animal diets (Hilton 1983), they are not currently mass-cultured on a scale large enough to allow for utility on a cost-effective basis.

Integration of Worm Culture and Composting with a RAS Operation using Aquaculture Biosolids

Although vermicomposting has been used to process a wide variety of organic wastes successfully, there has been relatively little investigation of its suitability, for aquaculture biosolids and fish manure. In initial trials at the University of Idaho, Rynk et al. (1998a, 1998b) attempted to evaluate the suitability of trout manure as a feedstock for vermicomposting. Generally, the project suggested that both composting and vermicomposting can beneficially recycle residues from aquaculture production, and that economic and environmental conditions of a specific farm would determine whether such processing is worth the effort (Buyuksonmez et al. 1998; Rynk et al. 1998a, 1998b). Earthworms required a moist aerobic environment at moderate temperatures; they did poorly in anoxic conditions and in materials with high concentrations of ammonia and salts. Generally, the worms didn't tolerate fresh manure. The worms performed better in "aged" fish manure and thrived in larger holding bins, compared to the slow growth when in small experimental containers with the same materials. The Idaho studies suggested that further investigation of the vermicomposting process for fish waste was necessary and that a period of acclimation appeared to be necessary before the worms would grow and reproduce when fed aquaculture biosolids.

In more recent work at UW-Milwaukee (NCRAC 2003), researchers used worms in previously-established beds rather than trying to rear them in the waste directly; they experienced no difficulty in inducing either red worm or cultured African nightcrawlers to feed on fresh RAS bead filter biosolids from a yellow perch (*Perca flavescens*) rearing operation. In addition, worms grew and reproduced as well or better than those fed dry commercial worm feed. Solid waste investigators working at Virginia Tech (Marsh et al. 2005) found biosolids from a tilapia (*Oreochromis* spp.) rearing RAS to be a successful food stock for vermicomposting. These studies confirm that aquaculture waste can be a suitable feedstock for worm production, provided that established worms are fed the biosolids in appropriate quantity and that their environment is within suitable tolerances for survival, with established, controlled bedding conditions that provide shelter from anoxic conditions due to over-application of raw waste.

To adapt vermicomposting to successfully process aquaculture biosolids, the operator needs to pay attention to the tolerances and needs of the worms. There are many worm-growing texts (see references) and extension guides (examples Bal and Curry 1977; Mason et al. 1992; Harper and Greaser 1994 ; Bogdanov 1996; Beetz 1999 & 2001; Sherman-Huntoon 2000; Sherman 2003; Shields 2006) that can aid the prospective worm culturist in understanding worm requirements and general culture methods.

There are also numerous Internet web sites and worm-grower newsletters with worm composting information:

- "The Worm web ring" at http://n.webring.com/hub?ring=wormdigest
- "Casting Call" at www.vermico.com/newsletter1.htm
- "Worm Digest" at www.wormdigest.org
- Rhonda Sherman's extension site at www.bae.ncsu.edu/people/faculty/sherman
- The Appropriate Technology Transfer for Rural Areas site at www.attra.ncat.org
- Trinity Ranch's Site at http://mypeoplepc.com/members/arbra/bbb/

The general concepts presented in these provide useful guidance but the prospective worm-grower will need to make some adjustments in feeding rates since the high moisture content biosolids from aquaculture differ from many of the typically suggested feed stuffs.

Choosing a Worm for Recycling

Several species of worms that are suitable for composting of organic waste are also bred commercially on a large scale for fish bait. Variations in size, reproductive potential, and environmental tolerances influence a particular species' utility for use in composting and for use as fish bait. In the NCR, RAS operations are generally housed indoor to achieve better climatic control for good fish growth. For this reason, indoor composting with the use of worm species that grow well at indoor RAS operating temperatures will require minimal additional climate control expenditure. Indoor culture also avoids the low seasonal temperatures that limit outdoor worm composting in the northern climes.

Recommended Candidates for Composting Worms: Life Histories and Environmental Tolerances:

Eisenia foetida, (Figure 1, upper) Common Names: red worm, tiger worm, brandling worm, manure worm.

This is the most commonly bred species used both for composting and fish bait on a large commercial scale. It is a rapidly reproducing worm, smaller sized, about 0.45 g (about 1,000/lb), with habits and tolerances well-suited for vermicomposting.

Eudrilus eugeniae, (Figure 1, lower) Common Names: African nightcrawlers, giant nightcrawlers.

Eisenia hortensis (syn. *Dendrobena veneta*), Common Names: Belgian nightcrawlers, European nightcrawlers

Perionyx excavatus, Common names: blue worm, Indian Blue, Malaysian blue, spike tail. Practical information on developmental timing and temperature tolerances for the above species is tabulated in Table 1.

Worm Life Cycle

Sexually mature worms possess a band or clitellum with both male and female sex organs present in an individual worm. During mating, individuals cross-fertilize each other to produce egg capsules or "cocoons" that may contain 1 to 20 individual young. These cocoons can be found by searching the bedding. They are egg-shaped with a small tube-like extension on one end, and are approximately the size of a grape seed. They are semi-translucent, pale yellow to light brown in color, and tend to darken with the development of the young in the capsule. Each

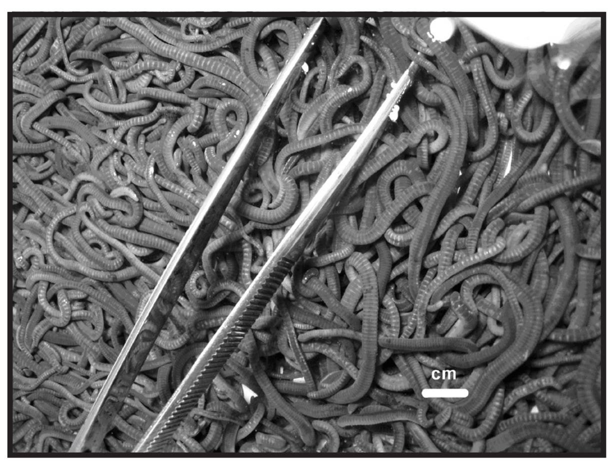

Figure 1.
Upper frame: Red worms (*Eisenia foetida)* at harvest.
Lower frame: African Nightcrawlers (*Eudrilus eugeniae*) at harvest.

can contain several developing young, with the number dependent on the species. Generally, survival at hatching may be three to four young from each egg capsule. Immature worms do not have the band or clitellum, which develops at maturation, starting the life cycle over.

Worm Beds and Composters

A wide variety of worm housing equipment is commercially available, although the beds may also be constructed from readily-available materials. Depending on the scale of operation, worm culture and worm composting are carried out in a wide variety of bedding structures from simple plastic pails, plastic children's swimming pools, or containers constructed of untreated wood or concrete block, to complex continuous-culture devices designed for large-scale worm production or waste management. Certain materials are unsuitable and should be avoided including: cedar, redwood, and other resinous woods, or soft woods like pine that the worms can eat through.

Worm production associated with a commercial RAS in the NCR will most likely be conducted indoors for climate control and will require an intermediate-to large-scale worm-rearing operation. Worm containers or bins should have holes for ventilation and to allow excess moisture to drain. Bin covers help retain moisture in the beds and shade the worms from light. Small to larger-sized household bins would be suitable for initial experimentation with worm growing. Numerous modular units could be adapted to growing schemes that separate worms in even-aged or sized-cohorts. Smaller modular units, such as ventilated plastic pails (Figure 2, lower frame) can be rotationally stocked with cocoons, permitting the separation and growing of uniform-age cohorts. At harvest, cocoons and new substrate could be continuously reused on a rotational basis. This allows for better inventory control of worm stocks and insures a culture density for a predictable harvest of both compost and uniformly-sized worms. Small modular units can be stacked to conserve space, but are more labor intensive than single, large, continuous-vermicomposting beds.

For large volumes of waste, large-scale continuous culture equipment similar to earlier designs

Table 1. Developmental timing and temperature tolerances of candidate species for vermicomposting.

	Reproductive Characteristics				Maximum Development & Growth Rate under Ideal Conditions			
Worm Species	Cocoons per adult per week	Hatching success	Hatchlings per cocoon	Net reproduction: young per adult per week	Days to cocoon hatch	Days to sexual maturity	Days from egg to maturity	**Temperature Requirements**
Eisenia foetida	3.8	83.2%	3.3	10.4	32-73	53-76	85-149	Optimum 25°C (77°F) Tolerance of 0-35°C (32-95°F)
Eisenia hortensis Syn. *Dendrobeana veneta*	1.6	81.2%	1.1	1.4	40-126	57-86	97-214	Optimum rather lower than *E. foetida* With less tolerance of extreme temperatures, but able to withstand a wide range of moisture
Eudrilus eugeniae	3.6	81%	2.3	6.7	13-27	32-95	43-122	Optimum about 25°C (77°F) But died below 9°C (48°F) and above 30°C (86°F)
Perionyx excavatus	19.5	90.7%	1.1	19.4	16-21	28-56	44-71	Optimum about 25°C (77°F) But died below 9°C (48°F) and above 30°C (86°F)

(This table was prepared from information from Edwards and Bohlen 1996.)

of Dr. Clive Edwards in the 1980s would probably be most suitable for processing the entire waste production of commercial scale RAS systems. An example that might be readily adapted to vermicomposting of aquaculture biosolids, can be seen on the Internet (www.oregonsoil.com/index.html). With continuous vermicomposters, the bedding material is placed on top of wet newspaper spread over a fairly large "hog wire" mesh, 5 to 10 cm (2 to 4 inch). Worms are attracted to the feed mainly in the upper few centimeters of bedding near the surface. Finished compost accumulates near the bottom of the bed and is fairly cohesive so that when shifted by mechanical scrapers it will fall through the bottom mesh. Finished compost is harvested from the bottom of the bin in this fashion. Smaller meshed wire hardware cloths are unsuitable for the bottom substrate since worm compost is too cohesive to pass through. For large-scale systems, the biosolids or feed are continually added to the top surface of the worm bed sometimes using a crane, thinly applying the food over the entire surface and covered with a thin layer of bedding to avoid attraction of insects and to reduce odor. This type of culture device has labor saving features and is best suited for continuous waste processing and compost production, but individual worm size will vary and growth of worms can be suppressed at high density. Worms need to be harvested on a regular basis at approximately 4-week intervals to achieve optimum population growth.

Figure 2.
Upper frame: "Worm Wigwam" style vermicomposters, used for continuous culture of redworms and African night crawlers using gravity-settled, bead-filter biosolids.
Lower frame: Ventilated modular vermiculture containers used in the replicated experimental evaluation of aquaculture biosolids on worm growth and survival.

In continuous culture, prediction of size distribution of harvestable worms and inventory control of the worm population is more difficult than when cohorts are separated. Since the modular small bins have the advantage of rearing separate and uniform cohorts of harvestable worms and the continuous rearing beds are more ideal for vermicomposting waste, it may be useful to use a hybrid strategy to integrate these methods into an RAS operation. The continuous culture could handle the bulk of the RAS biosolids with less concern about separating cohorts or the impact of high density on worm growth. During periodic harvesting, the under-sized worms could be stocked into modular, smaller-sized containers to promote a lower density for more rapid growth to an ideal size for use as bait.

Worm Bed Management

Worm bedding should consist of a variety of materials that retain sufficient moisture, yet drain well, and that resist compression to prevent anaerobic conditions. Suitable materials for bedding include: peat, sphagnum moss, shredded cardboard or paper, hardwood sawdust, dead leaves or chopped straw or hay, topsoil, composted manures, and combinations of these materials. Some bedding materials with highly-degradable materials can decompose and raise the temperature too high for worms. Such materials need to be pre-composted to pass through this heated phase, before they are suitable for worm bedding. For this reason bedding material should be set up and tested for temperature and pH changes before adding worms. Levels of 60 to 80% moisture are recommended in worm growing guides. As a practical guideline for moisture control, the bedding, when wetted, should have a moisture content that would only yield a few drops of water when squeezed by hand. The pH of the worm bedding must be maintained within a suitable range (6.8 to 7.2 for commercial worm culture). For this reason peat used alone tends to be too acidic. Because most organic bedding materials tend to become more acidic over time, the bedding should be tested periodically and small quantities of agricultural or garden lime (ground limestone, not hydrated lime) should be added to maintain proper pH. Conversely, if too much bedding or food with high protein or nitrogenous content is added, ammonia may be released to excessive levels too high to be suitable for worms. Bedding should be kept loose for proper aeration and replaced on a periodic basis since mature bedding tends to pack more densely.

All worm beds and bedding materials must meet the worms' requirements for shelter from extremes of rearing temperature, variations in pH, and moisture content. Adequate ventilation is necessary to regulate moisture content and to maintain aerobic conditions. Bedding depth for worm beds is generally kept within the range of 15 to 50 cm (6 to 20 inches). Cultured worms generally orient toward food that is worked into the bedding surface and, therefore, are most abundant near the food, just below the bedding surface. However they may spread throughout the bedding. Unfavorable bedding conditions can cause mass mortality or mass migration from the bedding, a useful warning to growers that conditions have deteriorated. Because worms are photonegative, having continuous low lighting around the covered beds will prevent their migration from the worm beds.

Stocking Rates and the Amount of Living Space needed for Worms

Edwards (1988) recommends stocking mature red worms at a ratio of about 1:10 biomass of worms to biomass of waste for the fastest processing of most wastes. However, for worm biomass production, cocoons or immature worms should be used rather than fully-grown or mature worms. University of Pennsylvania Extension (Harper and Greaser 1994) has made cost estimates and a sample budget of a small on-the-farm earthworm production operation. They recommend that bedding should be 2/3 topsoil and 1/3 decayed organic matter. Stocking range 1,100 to 5,400 worms/m^2 (100 to 500 worms/ft^2).

Although the inoculation of the beds with mature worms at high density will more quickly achieve maximum waste processing and compost production, at densities higher than 10,600 worms/m^3 (300 worms/ft^3), worm growth is inhibited (Mason et al. 1992). A smaller mass of younger worms could reach maturity and reproduce in a matter of weeks bringing the beds up to high density within a few months.

Sources of Worms

To find sources to purchase the initial worm stock, consult the "Earthworm Buyer's Guide", Shields Publications (2006), of Eagle River, Wisconsin, which periodically publishes their directory of North American earthworm hatcheries. Other extension vermicomposting resource guides and web pages such as "The Directory of Vermiculture Resources by State and Country: earthworms, supplies & information" (Sherman 2009) can be consulted.

Managing the Worm Bed Community and its Organisms

The worm bed consists of a complex interacting community of organisms that together accomplish the decomposition of organic wastes. In a properly-managed worm bed, the worms are sheltered from adverse conditions, are best able to assist in processing the waste material and the worm bed community is in proper balance. At the heart of the decomposition process are a variety of bacteria, fungi, and yeast-like organisms that are essential to the initial steps in the decomposition process. The worms consume these organisms along with the soil, bedding material, and partially-decomposed waste. The presence of these microbes contributes to the worm's nutrition. The desirable microbes for the worm bed are the aerobic (requiring oxygen) type. The tunneling of the worms themselves and the porous sponge-like nature of peat and other bedding material help ventilate the bed and help to maintain aerobic conditions.

If the bedding becomes too compressed and flooded, or too much raw waste is added causing the microbes to grow so fast that oxygen can't adequately get in the bed, the microbial community can shift to anaerobic (without oxygen) microbes that live on fermentation processes. The side products of anaerobic microbe metabolism are the obnoxious odors (e.g., rotten egg smell) associated with decomposition. A healthy aerobic worm bed will have an earthy odor like a rich, soil smell while an anaerobic bed will produce rotten carcass or sewage-like odors. Microbial activity also produces the heat that is the basis for the "thermophilic" action of conventional composting. Although some heat is helpful in maintaining good conditions for worm growth, it must not exceed the tolerance of the worms. Raw waste itself has too high of a capacity to grow microbes rapidly and to consume oxygen, so care must be taken in the rate that it is added to the worm bed so that living conditions in the bedding are suitable. The level of ventilation and the moisture content of the bed are important. Under adverse conditions, the worms will migrate from the bed, and/or die. Dead worms have a characteristic and highly-offensive odor as they decompose.

In addition to the characteristic bacterial and fungal flora of the worm bed community, there is a characteristic animal fauna. This includes a variety of microscopic protists, small soil nematodes, small species of white worms, mites, and specialized soil insects like springtails, ants, and flies attached to the waste. Small populations of insects naturally occur in worm beds but some will cause problems when they reach levels of infestation that are out-of-balance.

1. White or brown mites (*Uropoda agitans*, also called *Fuscuropoda agitans*) feed only on decaying or injured worms, but during periods of infestations they may devour much of the worm feed as well, causing poor worm growth and reproduction. Red mites are a natural enemy of earthworms, attaching themselves to suck blood and body fluids from the worms. Avoiding excess water and overfeeding will help protect these pests from taking over the beds. However, measures can be taken to control them if that happens. If they do appear, Sherman and Bambara (1997) suggest the following:Uncover and expose the worm beds to sunlight for several hours, and reduce the amount of water and feed. This creates an unfavorable environment so that the mites will migrate from the beds.
2. Place moistened newspapers or burlap bags on top of the beds to attract and accumulate the mites. Removal of the mite-infested paper or bags will reduce the population.
3. Heavily water, but not flood, the worm beds to drive the mites to the surface and cause the worms to burrow into the beds. Use a hand-held propane torch to scorch the top of the beds or use a light dusting of sulphur powder on the surface to kill the mites, but not harm the worms. The sulphur may increase the acidity of the worm bed.

Springtails (*Collembola*), small wingless insects that consume fungi, are found to be beneficial in the beds. Their numbers may be controlled by slightly drying out the beds. Soldier fly larvae may be found in large groups in the beds but are good decomposers and help recycle the waste, though care must be taken that they don't eat so much of the feed that the worms starve. If the worm beds become overrun with fruit flies, beneficial nematodes may be used to control the larvae. Beneficial nematodes may be purchased at a local garden center. Keeping worm beds covered can help reduce the incidence of fly invasion.

Worm Feeding

The quality of worm castings and compost is known to vary depending on the food source. Washed manures have the fine particulate organic matter and moisture that are ideal as worm feed stock. Typical RAS biosolids and waste have similar potential to provide a continuous and beneficial supply of worm feed stock. As microbes break down the food, the worms consume the microbes along with the feed. Guidelines for feeding waste during vermicomposting vary. Some suggest having one ft^2 of worm bed surface per pound of food waste to be processed. For a worm culture perspective, rather than an emphasis on waste disposal, Mason et al. (1992) recommend feeding dry worm chow at 0.5 lb per yd^2.

Others give values based on the biomass of worms present, such as: Worms will eat half their volume per day. This is a difficult value to determine with accuracy. In practice, the amount of feed is best adjusted to what worms will actually consume so that aerobic conditions will prevail. Too much food will cause excessive microbial fermentation, odor problems due to anaerobic and acidic conditions, and potentially excessively warm the worm beds. For good growth and reproduction, Harper and Greaser (1994) recommended that feed be applied in a thin layer into an actively growing bed every three to five days.

Recovery and Feeding of Aquaculture Biosolids as Worm Food

Back-flushed waste solids from the bead filter/clarifier of the University of Wisconsin/Great Lakes WATER Institute's (UW/GLWI) 25-m^3 (6,604-gal) recirculating aquaculture system (Figure 3) and, to a lesser extent, some solids from a 3.3-m^3 (872-gal) circular flow-through tank of yellow perch fingerlings (Figure 4) were obtained by gravity settling for use as worm food. A graduated conical-bottomed 560-L (148-gal) tank (Figure 3) was used to separate the solids from the remaining wastewater by gravity settling.

Over the 3-year period of this study, three cohorts of perch fingerlings were produced. The daily amount of settled biosolids recovered from the bead filter varied widely with a mean volume of 41 L (10.8 gal) and a range of 254 L (67 gal) and a median value of 30 L (8 gal). The total settled biosolids recovered over the 3- year period were 31.4 m^3 (8,306 gal). The biosolids were approximately 3.5% solid, with an approxi-

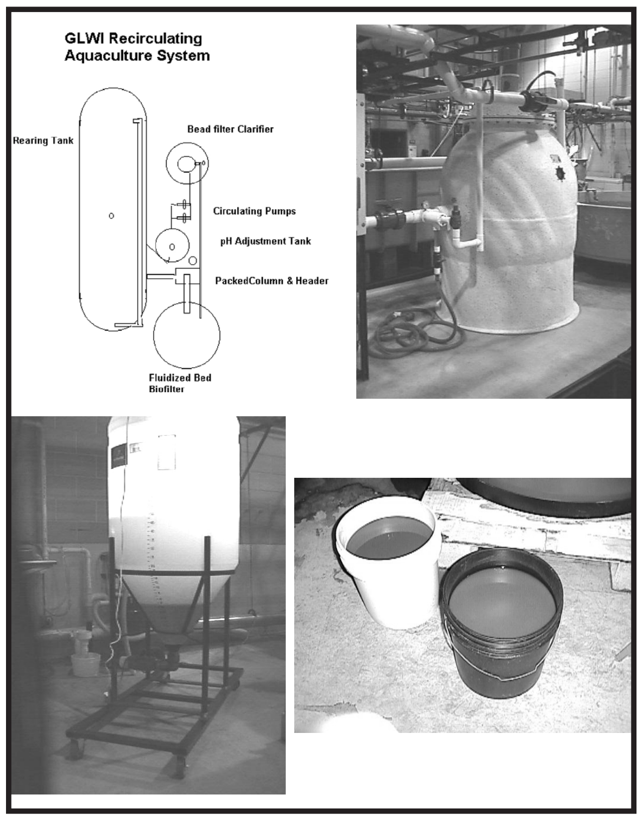

Figure 3. Schematic of the layout of the UW-Milwaukee GLWI Recirculating Aquaculture System (upper left). A close–up of the bead filter clarifier of this system from which the biosolids are backwashed (upper right). The conical bottomed settling tank (lower left) in which the biosolids were gravity settled and drained through a ball valve at the lower end of the cone. The collected biosolids (lower right) as they were applied to the worm beds.

mate dried weight of 1,099 kg (2,423 lbs) of recovered solids consisting principally of fecal material, waste food, and some microbial flocc, with possibly small amounts of sand from the biofilter. Yellow perch RAS bead filter biosolids were found to be a suitable feedstock for both "cultured" nightcrawlers and red worms. Because worm beds require adequate moisture, the high moisture content of settled aquaculture waste is advantageous. The biosolids act as feed for the worms and help to maintain the moisture content of the bedding as well. The solid waste recovered from double drain waste side-streams, rotating drums, filter backwashing, and siphoning from RAS clarification systems can be settled for approximately one hour up to several hours and then applied in a thin layer to the worm bedding.

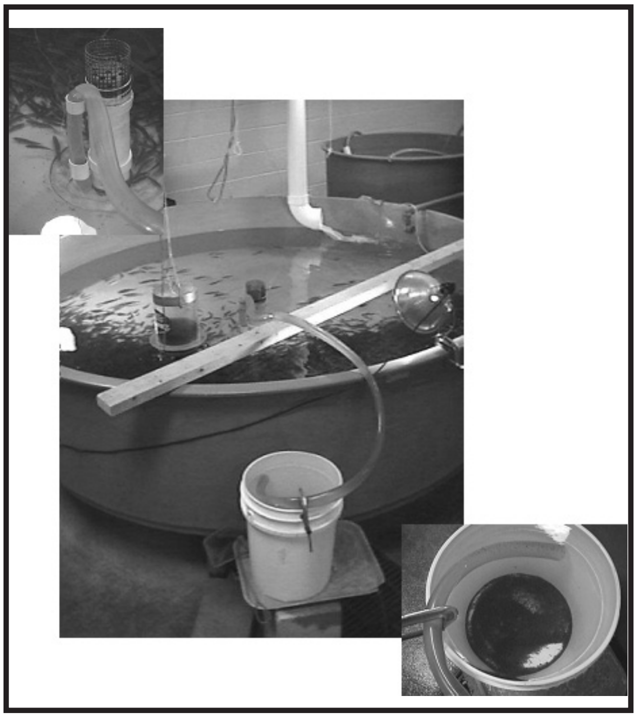

Figure 4. Low head siphon used to gather nearly intact feces and unused food from circular flow-through rearing tanks for use as worm food. Tank inflow was oriented to cause a circular flow in the tank, sweeping settled waste to the central sump. The tank sump was modified (upper left) with a concave poly resin insert that eliminated the right angles of the outer sump wall and permitted waste to accumulate next to the central standpipe. The inflow end of the clear vinyl siphon hose was attached to the standpipe with close fitting rings of PVC. The outflow of the siphon was adjusted to a low velocity by raising or lowering the collection pail (lower right) to just slightly below the water-level of the rearing tank effectively removing the waste intact. The continuous overflow of the collection pail was diverted to the floor drain. Pails of settled waste were periodically exchanged with the bulk of the water decanted and the remaining biosolids used as worm food.

Potentially, other types of wastes (e.g., tank cleanings and biosolids washed from rotating drum filters when settled by gravity) can be recovered at similar consistencies as the bead filter biosolids used for these investigations. Vermicomposting beds should be able to assist in further dewatering because the surface-applied solids are retained in the worm bed and excess moisture, with most of the solids removed, will drain through the bottom of the beds or evaporate.

Applying Aquaculture Biosolids as Worm Food

From January 2002 through December 2004, as part of a NCRAC workgroup investigating aquaculture wastes and effluents, investigators from UW/GLWI maintained continuous cultures of red worms *Eisenia foetida* and cultured tropical nightcrawlers, *Eudrilus eugeniae* using fish-rearing waste. These worms were principally fed settled bead filter biosolids from a yellow perch rearing recirculating system. Only during brief periods of interruption of the RAS operation, were these worms fed commercial worm meal. The settled bead filter biosolids were applied in thin layers that the worms would consume in several days time (Figures 5-10), controlling any excess feed which would result in anaerobic conditions and produce a noxious odor.

Two species of earthworm seed stocks were obtained: "cultured" nightcrawlers, *Eudrilus eugeniae*, (about 400 totaling 0.384 kg [0.847 lb]) and red worms, *Eisenia foetida* (about 500 totaling 0.081 kg [0.179 lb]). In January 2002, the worm stocks were introduced into separate, intermediate-sized, commercial, continuous vermicomposting bins of "worm-wigwam" style (Figure 2, upper). The surface area of each bin

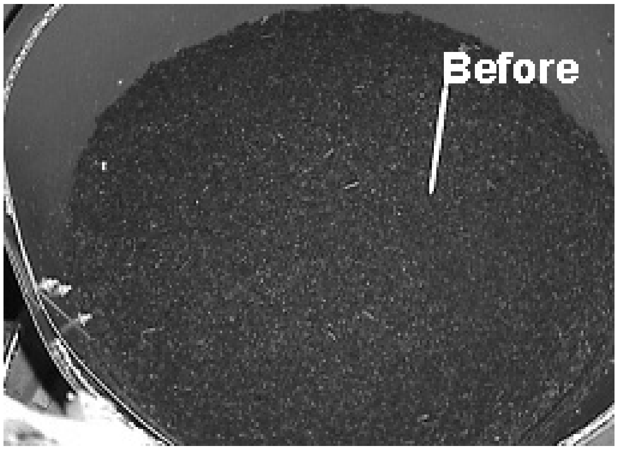

Figure 5. Time series of worms in a pre-established worm bed consuming RAS biosolids (10 L of wet biosolids).

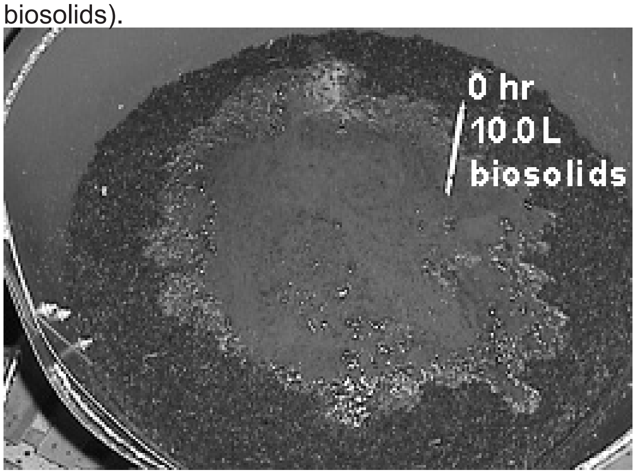

Figure 6. The biosolids were left on the surface but would normally be either incorporated into the bedding or covered with a thin layer of bedding to reduce the attraction of flies. (Note: worms are light-avoiding and the cover was removed only long enough to photograph their progress).

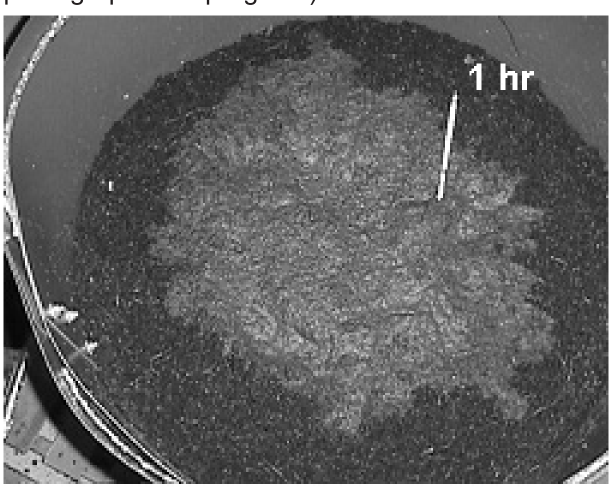

Figure 7. After 1hr, most of the excess water in the biosolids had drained into or through the bedding leaving a thin layer of food at the surface of the bedding. Worms had begun feeding on the margins of the biosolids layer.

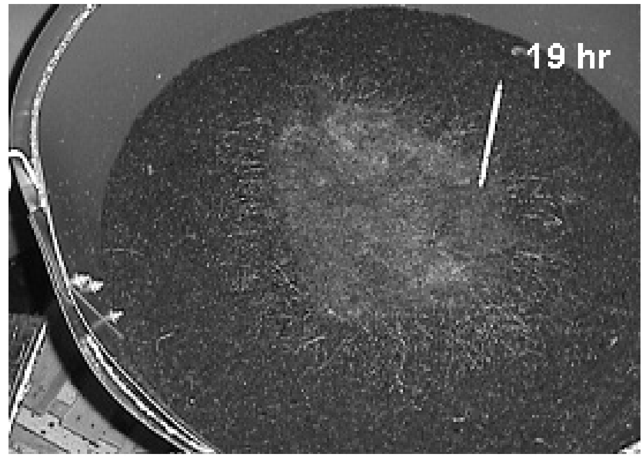

Figure 8. At 19 hrs after feeding, worms had been attracted to the margins and underside of the biosolids layer.

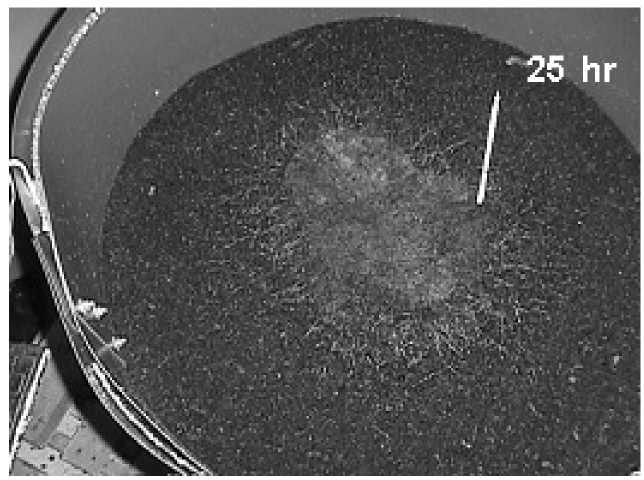

Figure 9. At 25 hrs after feeding, worms were feeding intensely at the edge of the biosolids layer.

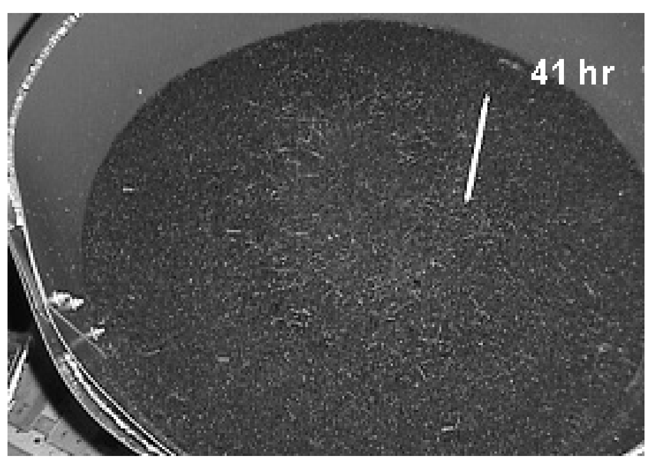

Figure 10. At 41 hrs after feeding, the entire biosolids layer had been nearly consumed by the worms.

was 0.66 m^2 (7.10 ft^2) and contained 75 kg (165 lb) of initial bedding material that ranged in depth between 10 to 20 cm (3.9 to 7.9 in).

The worm bedding absorbed most of the moisture in the biosolids. Occasionally, excess moisture would drip through the bottom of the bedding to be collected in a drip pan underneath the worm bed. Microbial activity during decomposition of the biosolids slightly raised the temperature immediately beneath the soil surface of the composters. These conditions tended to be localized to the layer of decomposing feed; within the worm bed there were adequate areas to allow the worms refuge from unsuitable conditions.

The two continuous vermicomposting beds utilized only a small percentage of the biosolids generated by the RAS. Typically, each bin surface area was fed 3 to 12 L (1.3 to 3.2 gal) of biosolids every 2 to 5 days, when the previous feeding was processed. At 96.5% moisture content, this represents feedings of dried biosolids at 0.16 to 0.63 kg/m^2 (0.3 to1.2 lb/yd^2). These feeding rates can be used to estimate the surface area of worm bedding required for handling the full-expected waste load of an RAS. Such a vermicomposting system would have to accept a daily mean biosolids volume of 41 L (10.8 gal) and at times of high fish density perhaps as much as twice the average 76 L (20 gal) per day.

Since it would take about 4 days before the surface that received the initial feeding could be fed again, the composter would have to be sized to accept around 304 L (80 gal) of wet biosolids, equivalent to 10.64 kg (23.2 lbs) dried biosolids per cycle of feeding. Such a vermicomposter should have a surface area of 9.7 m^2 (10.4 yd^2) to accept the mean biosolids volume and 16.9 m^2 (19.4 yd^2) for twice the average daily biosolids production.

Experimental Evaluation of Bead Filter Biosolids as Worm Food

In the summer of 2002, UW/GLWI researchers compared bead filter biosolids as a foodstuff to a commercial worm diet, for vermicomposting/vermiculture. In this experiment, RAS biosolids as a worm feedstock were as successful as, or outperformed, the commercial worm food. Buckets of nightcrawlers fed bead-filter biosolids increased 489% in overall worm mass with a 96% survival rate after four weeks. The weight of red worms fed bead filter biosolids increased 224% percent with 73% survival after four weeks. Between the second and fourth weeks, several buckets of both biosolids-fed and commercial food-fed red worms experienced some mortality. After four weeks, the weight of nightcrawlers fed commercial worm food increased 415% with a 99.8% survival. Red worms fed commercial worm food had a 63% survival rate and a worm biomass increase of 187% after four weeks. The fed worms grew much better (Figures 11 & 12) than the worms without supplemental feeding (these "non-fed" controls relied solely on the worm bedding community for sustenance). At four weeks, these unfed nightcrawlers increased only 154% with 100% survival and red worms increased 127% with a 97% survival rate.

Harvesting Compost and Worms

Periodically, the compost and the bait-sized worms must be separated from each other, and the cocoons and immature worms recovered to supply future worm stocks. Worms need to be harvested on a regular basis at approximately 4-week intervals to achieve optimum population growth. Strategies for harvesting (Sherman 2003) vary and often growers utilize worm behaviors such as their avoidance of light or their attraction to moisture, or food as aids in concentrating worms for harvest or for separating the majority of them from compost. Arrangements for harvesting vary depending on the size and type of operation. For a small indoor operation, a harvesting table could suffice. Bedding and worms from small modular containers could be spread on the table under bright lighting, causing the worms to concentrate deeper under the bedding. Thin layers of bedding can be successively skimmed from the top until the bottom container remains with the concentrated worms. The worms are graded by size, small ones returned for more growth and larger ones counted and transfered to containers with moist bedding and packaged for sale. Some growers place the harvested worms in moist sphagnum moss to purge them of adhering soil.

Because hand-picking worms from large volumes of bedding is too highly labor intensive to be cost effective on a large scale, various harvesting devices have been designed to sieve the finished compost/worm mixture through a series of various-sized hardware cloth meshes. The smallest mesh insures a finely-textured and uniform compost product. The next largest mesh collects cocoons and immature worms for further culture efforts and the largest mesh retains harvestable, bait-sized worms. In the UW/GLWI evaluation, the impact of hardwood sawdust and shredded paper as worm bedding additives was also examined, using the ventilated commercial production pails. All substrate types tested were successful in maintaining worm cultures. However, preliminary results suggest that the addition of sawdust allows better drainage and drying of the bedding and would probably reduce the labor required at harvest for separating and picking the worms from the bedding. Before harvesting, the worm bed should partially dry for several days

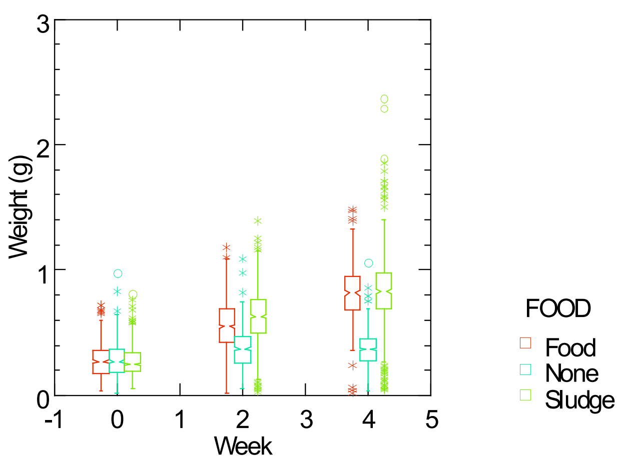

Figure 11. Box plots of the size distribution (individual weights in grams) of Red worms (*Eisenia foetida*) before, after 2 weeks, and 4 weeks of growth, comparing feedstocks: bead filter biosolids (Sludge), commercial worm food (Food), and no supplemental feeding (None) other than food value inherent in the worm bedding.

Each vertical box plot summarizes the data distribution for 15 to 400 individual worms. The central 50% of the worm sizes are included within the box. The notch shows the 95% confidence interval of the median value (i.e., 50% of the data is higher than this value and 50% is lower). Worm groups without overlapping notches for their medians can be considered significantly different. The range of values within the box is termed the hingespread. The "whiskers" (vertical lines) show the range of values included within 1.5 times the "hingespread". Each point beyond 1.5 hingespreads but less than 3.0 hingespreads is indicated by "x" and those beyond 3.0 hingespreads are represented by open circles.

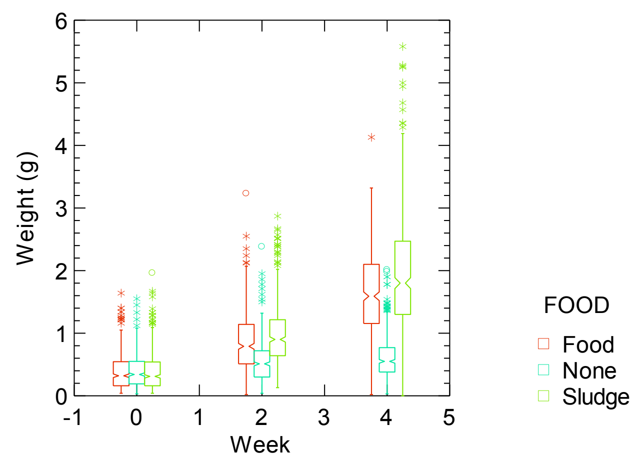

Figure 12. Box plots of the size distribution (individual weights in grams) of African Nightcrawlers (*Eudrilus eugeniae*) before, after 2 weeks, and 4 weeks of growth, comparing beadfilter biosolids (Sludge), commercial worm food (Food), and no supplemental feeding (None) other than food value inherent in the worm bedding.

Each vertical box plot summarizes the data distribution for 15 to 400 individual worms. The central 50% of the worm sizes are included within the box. The notch shows the 95% confidence interval of the median value (ie 50% of the data is higher than this value and 50% is lower). Worm groups without overlapping notches for their medians can be considered significantly different.The range of values within the box is termed the hingespread. The "whiskers" (vertical lines) show the range of values included within 1.5 times the "hingespread". Each point beyond 1.5 hingespreads but less than 3.0 hingespreads is indicated by "x" and those beyond 3.0 hingespreads are represented by open circles.

to make the compost more friable before screening.

Marketing Compost and Worms

Those attempting to market worms and compost produced from RAS waste should follow the advice of (Slocum and Frankel 2005):

- Talk to everyone, particularly those in the business. Talk to those who were successful and to those who were not.
- Meet growers, both novice and experienced. See their operations. Ask questions. Compare answers. Work with them if you can.
- Set up a small-scale vermiculture system and learn its management until you are confident of your ability to expand.
- Know your markets well before you invest a lot of money.

Worms can be sold directly to anglers and gardeners or wholesale to bait shops. Various types of containers can be used; about 500 bait worms will weigh close to a pound and fit into a one-gallon container. A quart can hold about 250 and a half-pint can hold about 50 red worms. Harper and Greaser (1994) recommend harvesting only enough worms for a few days' supply and storing them in moist bedding or peat moss.

The Center for Agribusiness and Economic Development at the University of Georgia has examined the compost and worm castings market (Doherty and McKissick 2000). They found that research into the market for worm castings is limited. The retail market for worm castings was found to be retail home and garden stores and sales through the Internet. They identified three types of products derived from worm castings that are sold retail: worm castings themselves, mixes of worm castings with other compost or soil, and a liquid product "compost tea" derived from worm castings. The worm castings were typically sold in 1 to 30 lb bags. Compost buyers generally rank elements of importance in the buying decision in the following order: quality, price, appearance, information and reliable supply (Sherman 1999).

Summary

This bulletin provides information on the potential of vermicomposting to process biosolids (i.e., the recoverable fecal material and uneaten food particles) from fish aquaculture to produce salable byproducts. With the goal of achieving a more sustainable and cost effective operation of recirculating aquaculture systems (RAS), worm-based methods for further processing of aquaculture generated biosolids are presented.

Information is provided on suitable worm species and resources regarding their reproduction, housing, and culture. Methods of recovering biosolids from tanks and bead filter clarifiers are presented. Potential uses and value of vermicompost and worms as products of biosolids processing are discussed.

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